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Recurrent radio activity in active galactic nuclei

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Abstract. There has been a growing body of persuasive evidence to indicate that AGN activity, powered by mass accretion onto a supermassive black hole, can involve multiple episodes. Thus thinking of jet activity as occurring within a unique brief period in the life of a galaxy is no longer valid. The most striking examples of AGNs with recurrent jet activity are the double-double radio sources, which contain two or more pairs of distinct lobes on the opposite sides of a parent optical object. On the other hand, we have now conclusive arguments that galaxy mergers and interactions are principal triggers for AGNs. Quite a number of examples of powerful radio sources hosted by galaxies with peculiar optical morphologies (tails, shells, dust-lanes, etc.) can be cited to support such a scenario. The structure and spectra of extended radio emission from radio galaxies, with sizes ranging up to a few Mpc, can provide a lot of information on the history of the central AGN activity, while the spectral and dynamical ages of these extended radio lobes could be used to constrain the time scales of recurrent AGN activity.

1. INTRODUCTION

The extragalactic radio sources have been known for about six decades (e.g. Cygnus A was identified with an optical galaxy by Baade and Minkowski in 1954). The commonly accepted mechanism of a radio source creation needs a spinning supermassive black hole (SMBH) with an accretion disk, from which energy is transferred to the extended lobes by narrow relativistic jets (Scheuer 1974). The coexistence of magnetic field and relativistic plasma leads to generating radiation through a synchrotron mechanism, which can be observed in the radio domain. The 0.01 – 100 GHz range luminosities of radio galaxies reach levels up to 10^{39} W.

Some long-established ideas about the basic properties of radio sources have had to be modified recently. It is well known that the jet activity ($\lesssim 10^8$ yrs), as compared with the life of the parent galaxy ($\sim 10^{10}$ yrs), is rather short. However, as it will be explained further, this kind of activity can be resumed once and again, contingent on the physical conditions in the vicinity of the central SMBH.

The existence of peculiar sources which cannot be classified either as FRII or FRI (Fanaroff & Riley 1974) can be a signature of an intermittent AGN activity. These include radio galaxies with two (or more) pairs of lobes emerging from the same radio core and aligned along a common axis. This category of objects, called double-double radio galaxies (DDRGs; Schoenmakers et al. 2000), constitute a rare class of extragalactic radio sources (about 40 objects are known to date; for references see Saikia & Jamrozy 2009; Nandi & Saikia 2012). DDRGs apparently occur over a wide range of sizes, from hundreds of kpc up to more than a Mpc. The interruptions in the jet production mechanism could be possibly brought about by refueling of the central engine as well as by instabilities in the accretion disk. Another group of peculiar sources are radio galaxies with an 'X-shaped' morphology (Leahy & Parma 1992), in which the second low-surface brightness pair of lobes are oriented along a quite different axis, forming an X-like structure. Several authors have proposed a number of models to explain formation of these structures, interpreting the morphology as a result of hydrodynamic backflow, conical precession, fast realignment of the jet, existence of an unresolved binary AGN system with two pairs of jets, or interaction of the jets with some merger remnants within the host galaxy. It was suggested by Liu and his collaborators (Liu 2004; Liu et al. 2003, 2012) that there is a kind of evolutionary relationship between X-shaped objects and DDRGs. X-shaped structures may arise due to a realignment of the SMBH binaries interacting with the accretion disc. Next, the secondary black hole migrates inwards, disrupting the inner parts of the accretion disc. The gap in the accretion disc expands after the binary SMBH coalesces, interrupting jet formation, which can restart later, following the inflow of new material into the central region, and thus a DDRG is born.

Some radio galaxies grow to very large Mpc sizes. The four largest known objects of this kind are shown in Fig. 1. Interestingly enough, there are many such giant sources among DDRGs. Machalski et al. (2011) consider the possibility that the structure of the largest radio galaxy J1420–0545 is formed by a restarted jet activity rather than the primary one. This hypothesis is motivated by the unusual morphological properties of the source, suggesting almost ballistic propagation of powerful jets in an extremely low-density environment.

Another curious fact is that one of the DDRG J1409–0302 is hosted by a disk galaxy (Hota et al. 2011). Therefore, it is not true that the hosts of powerful radio sources are exclusively elliptical galaxies. One more exception among late type galaxies to possess large scale jets is B0313-192 (Ledlow et al. 1998).

2. GALAXY MERGERS AND REPEATED JET ACTIVITY

There is much evidence to strongly connect the triggering of AGN and gravitational interactions between nearby galaxies (e.g. Koss et al. 2010). A number of hosts of radio galaxies show signatures of tidal interactions, such as tails, bridges, shells, and double nuclei. These tidal encounters

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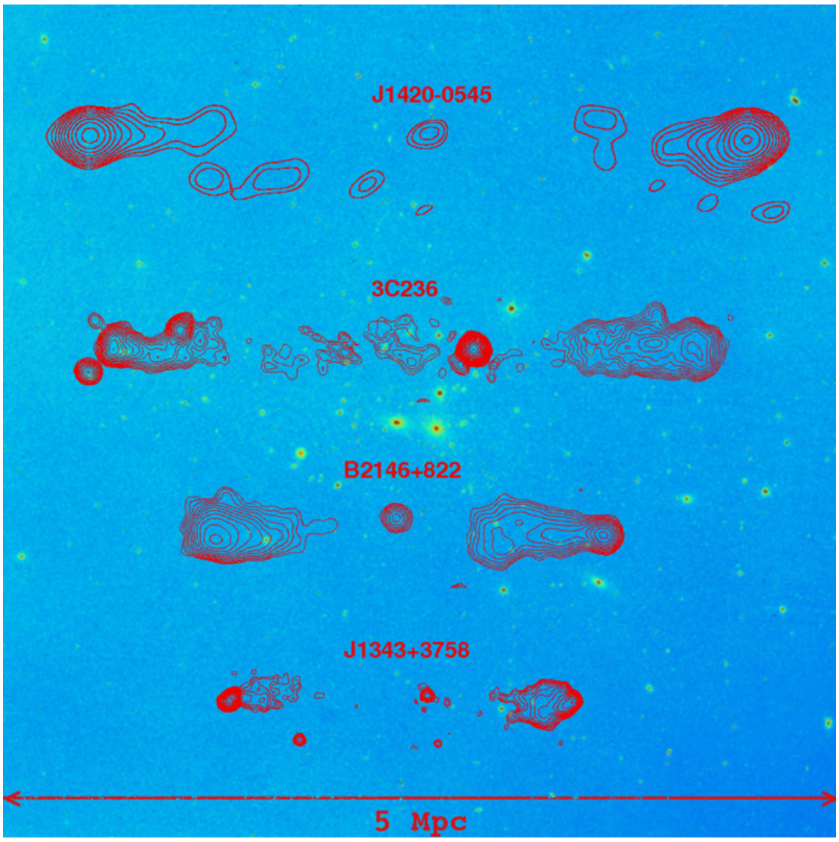

Figure 1. The four largest radio galaxies: J1420–0545, 3C236, B2146+822 and J1343+3758. Radio contour maps of the sources are overlaid on the optical DSS image of the Coma Cluster of galaxies. The scale of 5 Mpc is given in the bottom of the image.

can lead to large increases in the amount of material being fed to the central black hole, thereby triggering jet emission. A direct indication for two massive galaxies' merger should be the presence of SMBH binaries in the centres of at least some galaxies. The question is whether there are any observational examples to constrain them? We have direct evidence for the existence of radio jets arising from widely separated active SMBH binaries. 3C75 is a system of two SMBH separated by 8 kpc from each other (Hudson et al. 2006). An instance of a triple radio source is PKS 2149–158, where the closest cores are located within 13 kpc of each other (Guidetti et al. 2008). Unfortunately, because only few cases of actual mergers have been examined to date, the nature of the triggering events is still not well understood. For example, it is not clear at which stage of merging the onset of the radio activity takes place. In order to obtain more information on the AGN activity and its association with a merger event, a thorough study of properties of a radio structure could be essential. One suitable candidate for such an investigation is the galaxy CGCG 292–057.

2.1. CGCG 292–057

The optical image of CGCG 292–057 (see Fig. 2) clearly shows that this galaxy cannot be classified into any of the Hubble main classes. Its structure with bright extended nucleus surrounded by tidal features and tails confirms that the parent is a merger galaxy. It is a low-ionization nuclear emission-line region galaxy with a black hole of relatively low mass of $10^{8.5}$ $M_{\odot}$, and possibly double-peaked narrow emission lines. CGCG 292–057 is the only radio galaxy to manifest both a double-double and an X-like radio morphology, and which has also been identified with a merger galaxy. The total 1.4 GHz flux of the entire source corresponds to the power of 2×10^{24} WHz^{-1}, which makes it a transition FRI/FRII source. Actually, both the known X-shaped and DDRGs are low-luminosity FRII or FRI/FRII radio sources. The 270-kpc-long outer lobes are highly polarized, which is also typical of X-shaped sources. The arm-length ratio of the 23-kpc central lobes is about 1.54 and its peak-flux ratio is 1.50. This corresponds to an inclination angle of the radio structure to the line-of-sign of about 80 degrees. It seems, however, from the optical image of the host, that it is almost a face-on galaxy. The uniqueness of CGCG 292–057 is also due to the apparently short time-scale of the galactic merger, its subsequent jet reorientation and restarted activity, which allows us to simultaneously observe the results of these processes. The detailed study of this object – an ideal laboratory for the investigation of the recurrent jet activity in AGNs – is provided in Koziel-Wierzbowska et al. (2012).

3. ACTIVITY TIMESCALES

From the large-scale radio structure we can read the history of the central AGN behaviour. In order to understand the

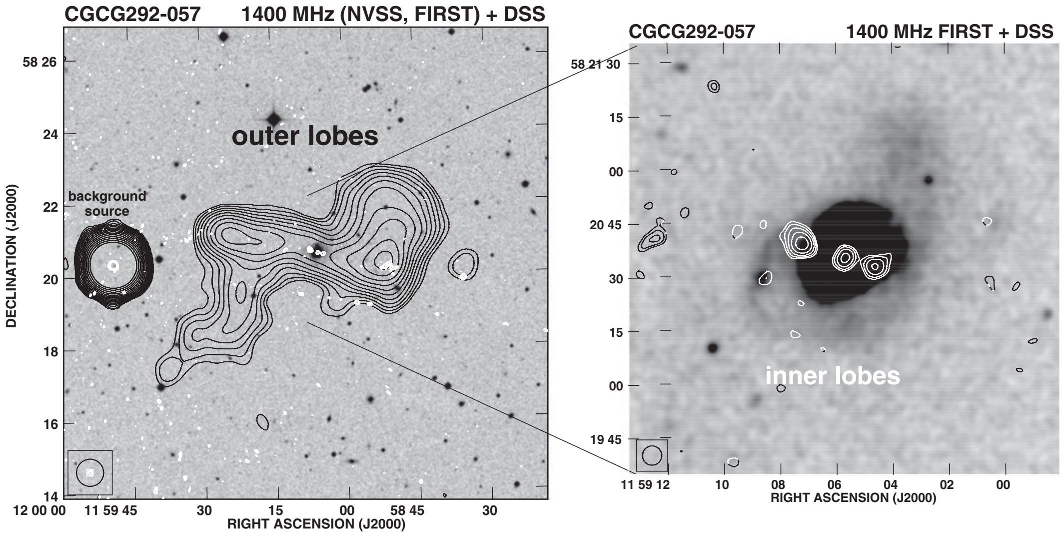

Figure 2. 1.4 GHz VLA images of CGCG 292–057. Left-hand panel: contour maps of the entire source from the NVSS (black) and FIRST (white) surveys overlaid on the optical field from the DSS. Right-hand panel: contour map of the central part of the source from the FIRST map overlaid on the DSS. The relative sizes of the beams are indicated by the circles in the bottom-left corner of each image.

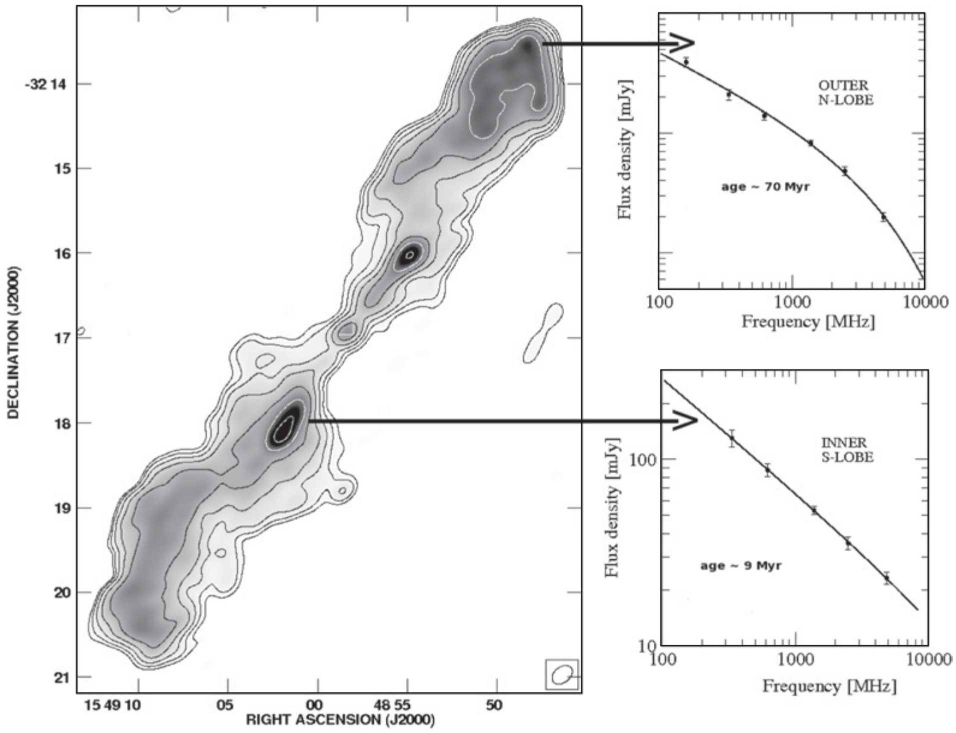

Figure 3. Left-hand panel: the 5-GHz VLA image of the double-double radio galaxy J1548–3216 (PKS 1545–321). Right-hand panel: spectra of the outer northern lobe, fitted with the Jaffe-Perola model (Jaffe & Perola 1973), and of the inner southern lobe, fitted with the continuous injection model (Kardashev 1962). The age of the respective structures is also indicated. For details, see Machalski et al. (2010).

cycles of AGNs and the phases of interruption of the jet flow, it is crucial to determine ages of the charged particles in different places within the radio lobes. The fact that in some radio galaxies two, or even three, pairs of lobes can be observed implies that the time required for the jet flow to cease is shorter than that for the outer lobes to fade. Therefore, since the lobes of extended radio sources can store the energy supplied by the jets for a time longer than the duration of the quiescent phase, the radio galaxies are able to preserve information on the past activity of the AGN.

The spectral age in different parts of the lobes, i.e. the time elapsed since the radiating particles were last accelerated, is determined using the classical synchrotron theory, which describes the time evolution of emission spectrum of a single population of particles with an initial power-law energy distribution. The power p of the distribution corresponds to the initial (injection) spectral index α_{inj}, which can be estimated from the observational low-frequency data. A spectral turnover (break frequency), $\nu_{\rm br}$, above which the radio spectrum steepens from the injected power law is related to the spectral (synchrotron) age. The values of α_{inj} and $\nu_{\rm br}$ could be found by the fit to the observed radio spectra.

Machalski et al. (2010) determined the ages and other physical characteristics of the outer and the inner lobes, as well as the properties of the surrounding environment during the original and restarted phases of the jet activity of the DDRG J1548–3216 (see Fig. 3). Using the multifrequency radio maps of this galaxy, the shape of the spectrum along its lobes was determined and the classical spectral-ageing analysis was performed. The age of the outer and the inner lobes of J1548–3216 is 70 and ∼ 9 Myr, respectively. These ages imply an average expansion speed along the jet axis of 0.012c in the outer lobes, and 0.058c in the inner lobes. The application of the analytical model of the jet's dynamics gave that the jet power during the restarted activity was about ten-fold smaller than that of the original jet.

Similar multifrequency analyses as that described above were performed for some other DDRGs, i.e. J1453+3308 (Konar et al. 2006), 4C29.30 (Jamrozy et al. 2007), J0041+3224 and J1835+6204 (Konar et al. 2012). One of the results obtained was that the average injection spectral index is much the same in two cycles of jet activity for J0041+3224, J1453+3308, and 4C29.30. It means that the values of α_{inj} are determined by the intrinsic properties of the sources. Konar et al. (2012) found that the duration of the quiescent phase of J0041+3224 is between 4 and 28 per cent of the age of the outer double (∼ 26 Myr). Analogously, in the case of J1835+6204 the duration of the quiescent phase of is less than 5 per cent of the duration of the previous activity (∼ 22 Myr). Hence, the off-time in the case of large-scale DDRGs could be of an order of few Myr.

The small number of well-studied DDRGs to date is a reason for a gap in our understanding of recurrent radio activity in AGNs, hence the phenomenon still awaits further multifrequency investigations and comprehensive explanation. The proposed new low-frequency radio telescopes (like e.g. LOFAR) will be excellent tools for investigating low surface-brightness and large angular-size diffuse cocoons surrounding the current active objects.

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